

Comparing Poynting flux dominated magnetic tower jets with kinetic-energy dominated jets

M. Huarte-Espinosa^a, A. Frank^a, E. G. Blackman^a, A. Ciardi^{b,c},
P. Hartigan^d, S. V. Lebedev^e, J. P. Chittenden^e

^a*Department of Physics and Astronomy, University of Rochester, 600 Wilson Boulevard,
Rochester, NY, 14627-0171*

^b*LERMA, Université Pierre et Marie Curie, Observatoire de Paris, Meudon, France*

^c*École Normale Supérieure, Paris, France. UMR 8112 CNRS*

^d*Rice University, Department of Physics and Astronomy, 6100 S. Main, Houston, TX
77521-1892*

^e*The Blackett Laboratory, Imperial College London, SW7 2BW London, UK*

Abstract

Magnetic Towers represent one of two fundamental forms of MHD outflows. Driven by magnetic pressure gradients, these flows have been less well studied than magneto-centrifugally launched jets even though magnetic towers may well be as common. Here we present new results exploring the behavior and evolution of magnetic tower outflows and demonstrate their connection with pulsed power experimental studies and purely hydrodynamic jets which might represent the asymptotic propagation regimes of magneto-centrifugally launched jets. High-resolution AMR MHD simulations (using the AstroBEAR code) provide insights into the underlying physics of magnetic towers and help us constrain models of their propagation. Our simulations have been designed to explore the effects of thermal energy losses and rotation on both tower flows and their hydro counterparts. We find these parameters have significant effects on the stability of magnetic towers, but mild effects on the stability of hydro jets. Current-driven perturbations in the Poynting Flux Dominated (PDF) towers are shown to be amplified in both the cooling and rotating cases. Our studies of the long term evolution of the towers show that the formation of weakly magnetized central jets within the tower are broken up by these instabilities becoming a series of collimated clumps which magnetization properties vary over time. In addition to discussing these results in light of laboratory experiments, we address their relevance to astrophysical observations of young star jets and outflow

from highly evolved solar type stars.

Keywords:

1. Introduction

Astronomical observations have established that collimated supersonic outflow, or jets, are ubiquitous. Young Stellar Objects (YSO), post-AGB stars, X-ray binaries and active radio galaxies show jets. The “central engines” of these flow cannot be directly observed due to insufficient telescope resolution. The launch and collimation of jets has been modelled in terms of a combination of accretion, rotation and magnetic mechanisms (Pudritz et al. 2007). The study of magnetized supersonic jets has recently reached the laboratory, where experiments have provided scale models of the launch and propagation of magnetized jets with dimensionless parameters relevant for astrophysical systems (Lebedev et al. 2005; Ciardi et al. 2009; Suzuki-Vidal et al. 2010). In combination with numerical simulations (Ciardi et al. 2007; Huarte-Espinosa et al. 2011), these experiments help us to resolve unanswered questions on jet physics. In particular the distinction between the physics of jet launch and that of jet propagation far from the engine. Since we cannot observe the former, it is important to identify distinct features of jets in the asymptotic propagation regime that can distinguish different engine paradigms. While both simulations and experiments now consistently reveal the promise, if not essentiality, of dynamically significant magnetic fields for jet launch, the correlation between the initial jet magnetic configuration and the stability of the flow far from the launching region is unclear.

The importance of the magnetic field flux relative to the flows’ kinetic energy divides jets into (i) Poynting flux dominated (PFD; Shibata & Uchida, 1986; Lynden-Bell, 1996; Ustyugova et al., 2000; Lovelace et al., 2002; Nakamura & Meier, 2004), in which magnetic fields dominate the jet structure, (ii) magneto-centrifugally launched (MCL; Blandford & Payne, 1982; Ouyed & Pudritz, 1997; Blackman et al., 2001; Mohamed & Podsiadlowski, 2007), in which magnetic fields only dominate out to the Alfvén radius. The observable differences between PFD and MCL jets are unclear, as are the effects that cooling and rotation have on PFD jets.

2. Laboratory experiments

Lebedev et al. (2005), Ciardi et al. (2007,2009) and Suzuki-Vidal et al. (2010) have carried out laboratory experiments of magnetized jets in the pulsed power facilities of Imperial College London. Lebedev et al. (2005) adjusted the dimensionless numbers (Reynolds, magnetic Reynolds and Peclet) of the plasma in these experiments in appropriate regimes for astrophysics. A critical ingredient of these laboratory experiments is the significant thermal energy loss of both the jets and the ambient medium plasmas; it plays a critical role in many astrophysical jet environments, e.g. YSOs. The experimental setup of Lebedev et al. (2005) consisted of a pair of concentric electrodes connected by a conical array of tungsten wires, of $13\mu\text{m}$ in diameter, inside a vacuum chamber. A TW electrical pulse (1 MA, 250 ns) was applied to this circuit. Such current causes ablation of the wires which results in the formation of a background ambient plasma (Figure 1a). This material is pushed above the wires by Lorentz forces then, while resistive diffusion keeps the current close to the wires. The current induces a toroidal magnetic field which at this stage is confined around the central electrode, below the wires. After the complete ablation of the section of the wires near the central electrode, the current switches to the plasma and creates a magnetic cavity (Figure 1b) containing a central jet. The jet's core is confined and accelerated upward by toroidal magnetic field pressure. The return current flows along the walls of the magnetic cavity which is in turn confined by both the thermal pressure and the inertia of the ambient medium plasma.

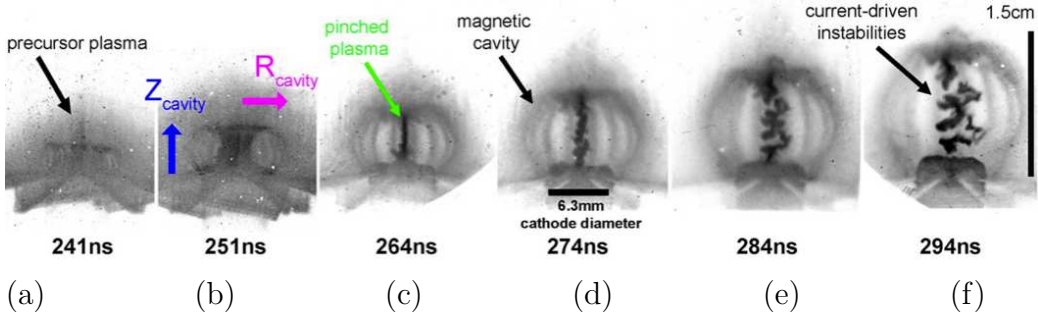


Figure 1: Soft X-rays images showing a time sequence of the formation of the background plasma (a), the expansion of the magnetic cavity (b), the launch of the jet (c), the development of instabilities in the central jet column (d) and the fragmentation of the jet (e,f). The wire array shows in the bottom part of the figures. Image taken from Suzuki-Vidal et al. (2010).

Then, the magnetic cavity opens up, the jet becomes detached and it propagates away from the source, in a collimated fashion, at velocities of order 200 km s^{-1} (Figure 1c).

Lebedev et al. (2005) found that the body of the jets in their experiments was significantly affected by the development of instabilities (Figure 1e). The outflows were fragmented into a well collimated set of clumps, or “bullets”, with characteristic axial non-uniformities (Figure 1e,f; Lebedev et al. 2005). Ciardi et al. (2007) reproduced these experiments using 3D non-ideal MHD numerical simulations carefully designed to model the laboratory components (electrodes and wires) and all the plasma evolution phases. The simulations of Ciardi et al. (2007) reproduced the experimental results of Lebedev et al. (2005) very well. The simulations clearly showed that during the final unstable phase of jet propagation the magnetic fields in the central jet adopted a twisted helical structure. Thus Ciardi et al. (2007) concluded the nano-metric jets of Lebedev et al. (2005) are affected by normal $m = 1$ mode perturbations.

3. Simulations

We use the Adaptive Mesh Refinement code AstroBEAR2.0 (Cunningham et al. 2009; Carroll-Nellenback et al. 2011) to solve the equations of MHD in 3D with cooling source terms. The grid represents $160 \times 160 \times 400$ AU divided into $64 \times 64 \times 80$ cells plus 2 adaptive refinement levels. We use extrapolation boundary conditions at the four vertical faces of the domain and at the top one, as well as a combination of MHD reflective and inflow conditions at the bottom face.

We will now briefly describe the setup of our simulations, see Huarte-Espinosa et al. (2012b) for a full description of the implementation. Initially, the gas is static and has an ideal gas equation of state ($\gamma = 5/3$), a number density of 100 cm^{-3} and a temperature of 10000 K. The magnetic field is helical, centrally localized ($\mathbf{B} \neq 0$ within $r, z < r_e$) and the magnetic pressure exceeds the thermal pressure inside the magnetized region. We use source terms to continually inject magnetic or kinetic energy at cells where $r, z < r_e$. We have carried out six simulations: three PFD magnetic tower jets and three hydrodynamic jets. For each case we calculated an adiabatic, a cooling and a rotating case. The hydrodynamic runs were implemented in such a way as to have same time average propagation speed and energy flux as the adiabatic PFD jet run. We use the cooling tables of Dalgarno & McCray (1972) for the

cooling case. For the rotating runs we applied a Keplerian rotation profile to the gas and magnetic fields located within $r, z < r_e$.

4. Results

4.1. Jet structure and stability

Our magnetic tower simulations consistently show that magnetic pressure gradients, alone, push field lines and plasma upward, forming magnetic cavities with low densities (Figure 2, all but right panel). PFD jets decelerate relative to the hydro ones; although both the PFD and the hydro jets have the same injected energy flux, the PFD case produces both axial and radial expansion due to magnetic pressure.

The cores of the PDF jets are confined by magnetic hoop stress, while their surrounding cavities are collimated by external thermal pressure. In contrast, the pre-collimated hydro jets can only expand via a much lower thermal pressure. Thus for our setup all of the energy flux in the hydro-case is more efficiently directed to axial mechanical power. It is worth mentioning that our hydro cases can emulate to some degree the asymptotic propagation regime of a jet that was magneto-centrifugally launched (e.g. Blackman 2007) which is

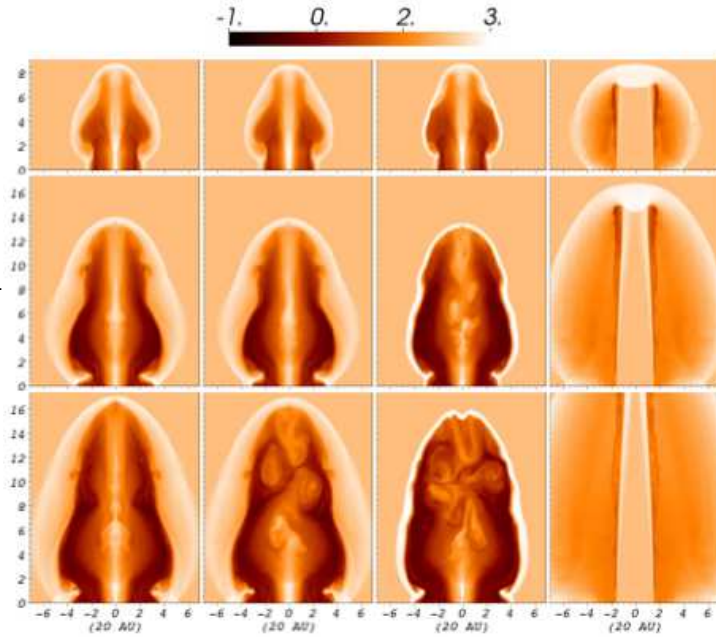


Figure 2: Logarithmic false color density maps of the adiabatic (1st column), rotating (2nd column) and cooling (3rd column) PFD jets. Hydrodynamic jet (4th column). From top to bottom the time is 42, 84 and 118 yr.

distinct from a PFD jet.

Regarding the structure of the jets, we find that the PFD jet cores are thin and unstable, whereas the hydro jet beams are thicker, smoother and stable. These are observationally distinguishable features. The base rotation and the cooling conditions that we explore (see end of Section 3) have mild effects on the propagation of the hydro jets, but strong effects on the stability of PFD jets.

Instabilities in our PDF jets are current driven; the jets carry high axial currents which return along their outer contact discontinuity. Lebedev et al. (2005) saw this current density distribution in their magnetic tower experiments. We find that the thermal to magnetic pressure ratio distribution, $\beta(\mathbf{X}, t)$, consists of a central high beta plasma column –the jets’ core– surrounded by the low beta plasma of the cavities (Figure 3). The growth rate of the current driven instabilities is accelerated by cooling, firstly, and by base rotation, secondly.

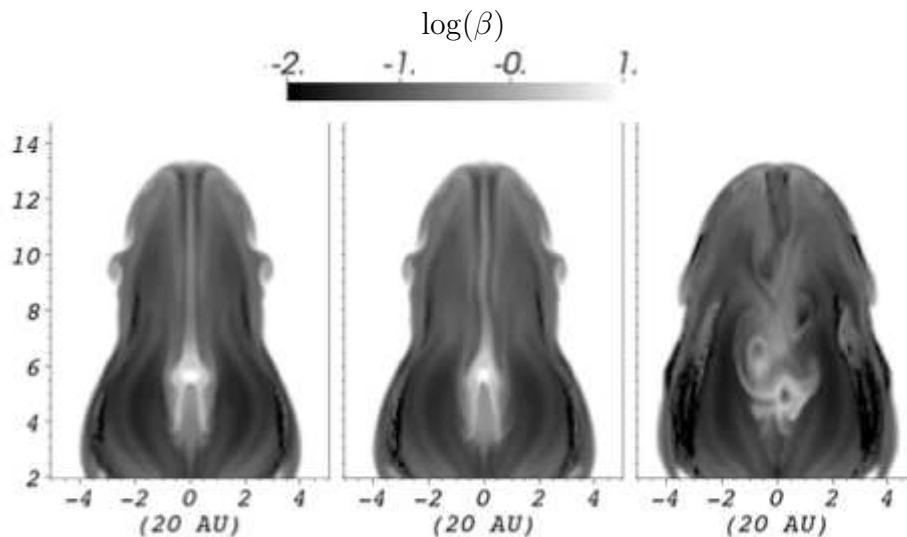


Figure 3: Thermal to magnetic pressure ratio of out PDF magnetic towers at time=84 yr. These are logarithmic false gray-scale maps of the adiabatic (left), the rotating (middle) and the cooling (right) jets.

At the core of these jets the axial magnetic field dominates over the

toroidal one. $|B_\phi/B_z| \ll 1$. Thus the columns' instability condition is given by

$$\left| \frac{B_\phi}{B_z} \right| > |(\beta_z - 1)kr_{jet}|, \quad (1)$$

where $\beta_z = 2\mu_0 P/B_z^2$, μ_0 is the magnetic vacuum permeability, P is the plasma thermal pressure and k^{-1} is the characteristic wavelength of the current-driven perturbations (Huarte-Espinosa et al., 2012b).

The cooling jet core consistently shows $\beta_z \sim 1$ which means that because of thermal energy losses it does not have sufficient thermal energy to damp the toroidal magnetic pressure. Hence kink perturbations grow exponentially. A different path to instability operates in the case in which we apply a Keplerian rotation profile at the base of the PDF jet. Rotation causes a slow amplification of the toroidal magnetic field, hence the left hand side of equation (1) increases slowly and so do the kink mode perturbations. The rotating jet is not completely destroyed by these perturbations, and their amplitude is about twice the radius of the central jet (see Huarte-Espinosa et al., 2012b for details), in agreement with the Kruskal-Shafranov criterion (Kruskal et al. 1958; Shafranov 1958).

4.2. Energy flux distribution

In Figure 4 we show logarithmic color maps of the distribution of the jet Poynting to kinetic flux ratio $Q(\mathbf{x}, t) = f_P/f_k$ as a function of time, where

$$\begin{aligned} f_P &= \int [\mathbf{B} \times (\mathbf{V} \times \mathbf{B})]_z dS, \\ f_k &= \int_s \frac{1}{2} \rho |\mathbf{V}|^2 V_z dS. \end{aligned} \quad (2)$$

These integrals are taken over the area of the jets' beam.

We consistently see the core of the jets is dominated by kinetic energy flux ($Q < 1$, blue region), while the bulk of the beams is PFD ($Q > 1$, red region). Such distribution is consistent with the one in the laboratory jets of Lebedev et al. (2005, section 2). The time average mean Q of our magnetic tower beams is ~ 6 , in agreement with the magnetic towers of (Kato et al., 2004, see their Fig. 3b, bottom).

A very interesting result of our simulations is the long term evolution of PFD jets which yields a series of collimated clumps, the magnetization properties of which vary over time and distance from the engine. PFD flows may thus eventually evolve into HD jets at large distances from the central engine. A future avenue for this investigation is a comparison of the $Q(\mathbf{X}, t)$ distribution between our magnetic towers –where $Q > 1$ for the parameters explored– and models of jets created by MCL processes; while MCL jets begin with $Q > 1$ on scales less than the Alfvén radius, in the asymptotic limit the kinetic energy flux comes to dominate the flux of electromagnetic energy leading. Simulations of MCL launching in which the flow is cold and gas pressure can be ignored show typical values of $Q \sim 0.7$ at observationally-resolved distances from the engine (Krasnopolsky et al. 1999, 2003).

Changes in the distribution of $Q(\mathbf{X}, t)$ are quite relevant for astrophysical jets. E.g. Hartigan et al. 2007 have shown that in YSO, and perhaps in planetary nebulae jets as well, some mechanism may be needed to reduce the magnetization of plasma close to the jet source. If these flows began as magnetic towers then the disruption of the central jets via kink modes may provide a means to produce collimated high

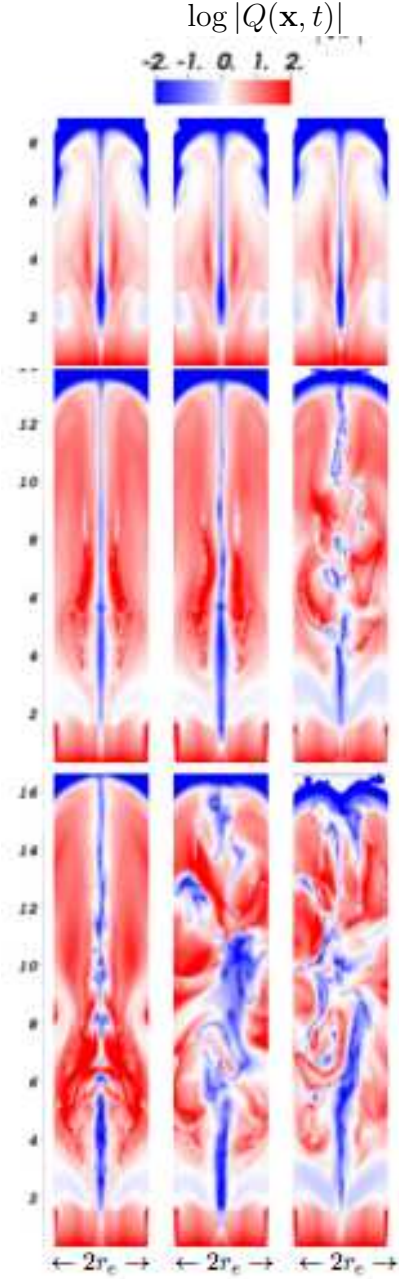


Figure 4: Logarithmic color maps of the distribution and evolution of the magnetic towers Poynting to kinetic flux ratio.

beta clumps of material as is observed in HH flows. Our calculations are thus the first steps towards distinguishing between different launch mechanisms by providing descriptions of asymptotic flow characteristics where observations might be possible, specially with the next generation of telescopes, e.g. ALMA.

5. Conclusions

Our magnetic tower jet simulations are in good agreement with the laboratory experiments of Lebedev et al. (2005). In both investigations jets: (1) carry axial currents which return along the contact discontinuities, (2) the cores have a high β plasma, (3) the beams and cavities are PFD, (4) are eventually corrugated by current driven instabilities becoming a collimated chain of magnetized “clumps” or “bullets”. We stress the similarity between our models and the laboratory experiments because our implementation was not tuned to represent the laboratory results at all. The laboratory experiments and the simulations support each other then, as well as the conclusion that both are revealing generic properties of PFD outflows.

Our simulations show that PFD jet beams are lighter, slower and less stable than pre-collimated asymptotically hydrodynamic jets. The latter might represent the asymptotic propagation regimes of magneto-centrifugally launched jets. We find current-driven perturbations in the PFD jets, which for the regimes studied are amplified by cooling, firstly, and by base rotation, secondly. This happens because shocks and thermal pressure support are weakened by cooling, making the jets more susceptible to kinking. Base rotation, on the other hand, amplifies the toroidal magnetic field which in turn exacerbates the kink instability. Eventually the instabilities cause the corrugation of the jets’ beam. PFD jets become a collimated chain of magnetized “clumps” or “bullets” then.

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